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HEAT SINK EFFECTS IN VARIABLE POLARITY PLASMA ARC WELDING

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INTRODUCTION

The space shuttle external tank is fabricated by the variable polarity plasma arc (VPPA) welding process. In VPPA welding a noble gas, usually argon, is directed through an arc to emerge from the torch as a hot plasma jet. This jet is surrounded by a shielding gas, usually helium, to protect the weld from contamination with air. The high velocity, hot plasma jet completely penetrates the workpiece (resembling a line heat source) when operated in the "keyhole" mode. The metal melts on touching the side of the jet, as the torch travels in the perpendicular direction to the direction of the jet, and melted metal moves around the plasma jet in the keyhole forming a puddle which solidifies behind the jet.

Heat sink effects are observed when there are irregularities in the workpiece configuration especially if these irregularities are close to the weld bead. These heat sinks affect the geometry of the weld bead, i.e. in extreme cases they could cause defects such as incomplete fusion. Also, different fixtures seem to have varying heat sink effects.

Steranka (2,3) has worked on heat sink effects in VPPA welding, but he only experimented on one configuration where the heat sinks were attached externally to the workpiece and developed a complicated model.

The objective of this research is to study the effect of irregularities in workpiece configuration and fixture differences (heat sink effects) on the weld bead geometry with the ultimate objective to compensate for the heat sink effects and achieve a perfect weld. Experiments were performed on different workpiece geometries and compared to approximate models.

MODELS

Nunes (1) has introduced an approximate model to express the diameter d of the weld puddle, i.e. the width of the weld bead:

$$d = 4.492\,\frac{\alpha}{V}\,e^{\frac{-2\pi k w (Tm - To)}{\eta P}} \qquad [1]$$

where α = thermal diffusivity of the workpiece metal
V = velocity of welding torch
k = thermal conductivity of the workpiece metal
w = thickness of the workpiece
Tm = melting temperature of the weld piece metal
To = ambient temperature of the workpiece
ηP = fraction of power absorbed by the workpiece

Equation [1] is applicable to an infinite adiabatic plate, i.e. it ignores the heat losses from the workpiece due to radiation and convection to the air and the heat losses due to conduction through the fixture and grounding connections.

From equation [1] changes in the weld diameter due to ambient temperature changes ΔTo (caused by heat sinks) can be calculated as follows:

$$\frac{\Delta d}{d} = e^{\frac{2\pi k w \Delta To}{\eta P}} - 1 \qquad [2]$$

EXPERIMENTS

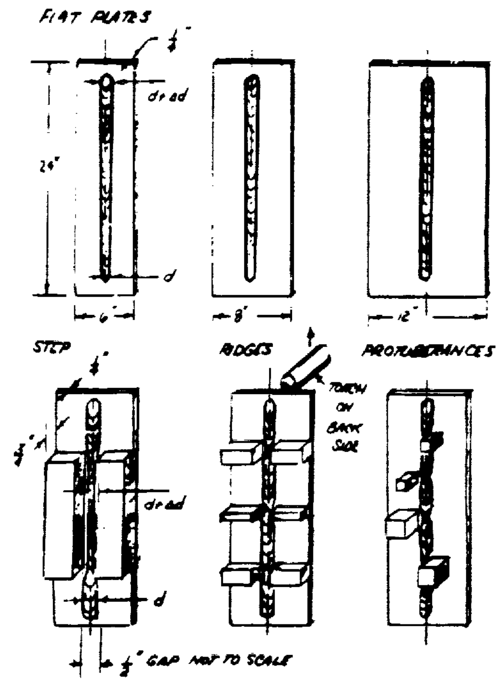

Fig. 1: Configuration of heat sinks

Six, 24 in. long, aluminum 2219 T87 plates were prepared for welding. Three plates were flat, 0.25 in. thick, with widths 6, 8, and 12 in., respectively. The remaining three plates, 24 in. by 8 in., were milled down according to desired shapes, as shown in Figure 1, from 0.75 in. to 0.25 in. as follows:

Plate with step: The step, 0.5 in. thicker than the rest of the plate, had a length of 12 in. leaving 6 in. at the start and end of the plate. The width of the step extended from the edges of the plate to 0.25 in. from the longitudinal center of the plate, thus leaving a 0.5 in. gap at the center.

Plate with ridges: Three ridges, 0.5 in. thicker than the rest of the plate, extended through the width of the plate except for 0.5 in. gap at the center. One ridge 0.5 in. wide was located at the middle of the plate (centered 12 in. from the start), the other two (1.5 in. wide started 5 in. from the bottom and top edges of the plate.

Plate with protuberances: As in the previous two cases this plate was milled down from 0.75 in. to 0.25 in. leaving four square protuberances. The first protuberance is 2 by 2 in., and starts 5 in. from the bottom of the plate and 0.25 in. to the right of the longitudinal center line. The second, third and fourth protuberances, each starts 3 in. after the previous one ends. The second (2 x 2 in.) and the third (1 x 1 in.) protuberances are located 1 in. to the left of the center line, while the fourth protuberance (1 x 1 in.) is 0.25 in. to the right of the center line and 4 in. before the top of the plate.

One pass, bead on plate welds were performed on all six plates, without wire feed. The plates were welded vertically starting at the longitudinal center, 1 in. above the bottom edge of the plate, with the torch located 3/8 in. away from the flat side of the plate. All welding conditions were kept the same for the six plates, e.g. the weld length was 22.22 in., the torch velocity 11 in./min. and the power was set to produce 4185 W with fluctuations on the order of ±0.2 kW.

In order to minimize heat losses that would mask the effect of plate size the sides of the plates were insulated with Acculam (high pressure phenolic laminate) except for 4 in. along the center, which were not insulated to avoid interference with welding. This eliminated heat sink effects from the fixture, and necessitated joining the power supply coupling and grounding lines to the bottom of the plates.

RESULTS AND DISCUSSION

The crown and root diameters of the welds were measured with a vernier caliper at intervals of 0.38 in. The standard deviation in measurement was almost 0.02 in. compared to diameters less than 0.3 in. This high standard deviation arose from human error in measuring the diameters due to illumination and reflection of the metal, to avoid this problem representative samples were cut and macroscopically treated then measurements of the weld were taken with a microscope, a summary of these measurements is given in table 1.

TABLE I: Microscopic Weld Bead Dimensions.

TIME min.sec	POSITION in.	ARC POWER kW	CROWN DIAMETER in.	ROOT DIAMETER in.	AVERAGE DIAMETER in.	WELD HEIGHT in.	PLATE THICKNESS in.
TWELVE	INCH	WIDE	FLAT	PLATE			
0.26	3.47	4.10	0.3202	0.2906	0.3054	0.2877	0.2467
1.50	18.90	4.17	0.3191	0.2522	0.2857	0.2910	0.2502
EIGHT	INCH	WIDE	FLAT	PLATE			
0.24	3.10	4.11	0.3121	0.2392	0.2757	0.2369	0.2456
1.48	18.52	4.14	0.3187	0.2430	0.2809	0.2812	0.2458
SIX	INCH	WIDE	FLAT	PLATE			
0.24	3.10	4.21	0.3148	0.2702	0.2925	0.2935	0.2490
1.48	18.52	4.12	0.3165	0.2575	0.2870	0.2863	0.2501
PLATE	WITH	STEP					
0.24	3.10	4.15	0.3335	0.2583	0.2959	0.2748	0.2543
0.34	4.95	4.15	0.2872	0.2137	0.2505	0.2175	0.2540
0.38	5.67	4.17	0.2924	0.1688	0.2306	0.2709	0.2541
1.04	10.47	4.17	0.3044	0.1477	0.2261	0.2566	0.2574
1.38	16.69	4.17	0.3197	0.1576	0.2387	0.2857	0.2590
1.48	18.52	4.17	0.3271	0.2190	0.2731	0.2958	0.2584
PLATE	WITH	RIDGES					
0.24	3.10	4.11	0.3143	0.2412	0.278	0.2931	0.255
0.34	4.95	4.17	0.2964	0.1435	0.220	0.2561	0.2576
1.06	10.82	4.18	0.311	0.1678	0.239	0.2852	0.2594
1.36	16.33	4.08	0.3013	0.1883	0.245	0.2748	0.2544
1.50	18.90	4.11	0.3037	0.2386	0.271	0.2949	0.2586
PLATE	WITH	PROTUBRANCES					
0.24	3.10	4.20	0.2997	0.2220	0.2609	0.2940	0.2640
0.38	5.67	4.17	0.2970	0.1838	0.2404	0.3081	0.2734
1.04	10.47	4.09	0.3064	0.2332	0.2698	0.3038	0.2667
1.26	14.49	4.12	0.4065	0.2379	0.3222	0.2978	0.2618
1.48	18.52	4.17	0.3116	0.1903	0.2510	0.3063	0.2668

From table II it is obvious that the theoretically estimated variations in diameters are higher than the measured values. In an attempt to explain discrepancies rough estimates of heat losses, not included in the theoretical estimates, were performed. The heat lost by conduction through the power supply coupling and grounding connections is approximately 2% of the heat absorbed. Convection from the workpiece is roughly in the proximity of 10%. Heat lost by radiation from the workpiece is expected to be very high near the moving heat source and diminish rapidly towards the edges of the plate. An average temperature can not be used to estimate the radiative heat losses, because these vary with the fourth power of the local absolute temperature.

TABLE II: Comparison Between Measured and Estimated Variations in Diameters Due to Taper or Heat Sink Effects.

PLATE	MEASURED $\frac{\Delta d}{d}$ *	ESTIMATED $\frac{\Delta d}{d}$	REMARKS
Flat, 12 in. wide	-0.0800 -0.0276	0.185	Variation in thickness is evaluate.
Flat, 8 in. wide	0.0075 0.0357	0.322	
Flat, 6 in. wide	-0.0233 0.0267	0.434	Variation in thickness is evaluated.
Step	-0.1534 -0.1800	-	Start of step.
	-0.2207 -0.1213	-0.632	0.5 in. from start of step.
	-0.2359 -0.1542	-0.632	Middle of step.
	-0.1933 -0.0811	-	close to end of step.
	-0.0771 -0.0032	-	Flat, 1.75 in. from end of step
Ridge	-0.2081 -0.1661	-0.657	Bottom wide ridge.
	-0.1382 -0.0813	-0.657	Middle narrow ridge.
	-0.1188 -0.0900	-	Start of top wide ridge.
	-0.0238 -0.0084	-	Flat, 1 in. after end of top ridge
Protuberance	-0.0786 -0.0115	-0.172	First (2x2 in.).
	0.0341 0.0337	-0.017	Second (2x2 in.).
	0.2350 0.1173	-0.03	Third (1x1 in.)
	-0.0380 0.0040	-0.119	Fourth (1x1 in.)

*Top measurement is based on the average diameter of the weld, while the bottom is based on a combination of the average diameter and weld height.

Time ran out before a theoretical estimate of radiation losses could be completed, but a large value for radiation losses might explain the difference in theoretically estimated taper and observed taper.

CONCLUSION

The approximations used overestimated the change in weld diameter, possibly in the case of taper calculations at least, due to heat losses by radiation. Convection to the surrounding and conduction through the connections from the workpiece were not powerful enough heat sinks to substantially affect the theoretical computations. Also, the exact energy transferred from the arc to the workpiece is not known. In order to better understand the observed discrepancies between theory and observation it is proposed that detailed observations of the temperature fields within the workpiece be taken during welding.

REFERENCES

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